

What to do with all the LHC data once it's there

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Outline

Why BSM?

Supersymmetry

Masses

Parameters

Spins & cascades

Spin & jets

Standard–Model effective theory

TeV–scale supersymmetry

Masses from cascades

Underlying parameters

Spins from cascades

Spins from jets

Standard–Model effective theory

A brief history of our Standard–Model mess...

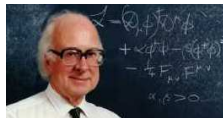
- Fermi 1934: theory of weak interactions $[n \rightarrow pe^- \bar{\nu}_e]$
($2 \rightarrow 2$) transition amplitude $\mathcal{A} \propto G_F E^2$
unitarity violation
pre-80s effective theory for $E < 600$ GeV
- Yukawa 1935: massive particle exchange
Fermi's theory for $E \ll M$
four fermions unitary for $E \gg M$: $\mathcal{A} \propto g^2 E^2 / (E^2 - M^2)$
unitarity violation in $WW \rightarrow WW$
current effective theory for $E < 1.2$ TeV [LHC energy!!]



Standard–Model effective theory

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- Higgs 1964: spontaneous symmetry breaking
unitarity for massive W, Z
unitarity for massive fermions
fundamental scalar below TeV [mass unknown]
- 't Hooft & Veltman 1971: renormalizability
beware of $1/M$
gauge theories without cut-off
truly fundamental theory



Standard–Model effective theory

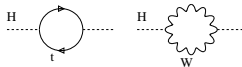
Our Standard Model

- gauge theory $SU(3) \times SU(2) \times U(1)$
 - massless $SU(3)$ and $U(1)$ gauge bosons
 - massive $SU(2)$ gauge bosons [spontaneous symmetry breaking]
 - massive Dirac fermions [via Yukawas]
 - perturbatively renormalizable Lagrangian [no effective theory]
 - one missing piece: Higgs [fundamental? minimal? mass?]
- ⇒ defined by particle content, interactions, renormalizability
- ⇒ **truly fundamental theory at high energies**

How complete experimentally?

- dark matter? [solid evidence! — for weak–scale new physics?]
 - $(g - 2)_\mu$? [possible evidence for weak–scale new physics?]
 - quark mixing — flavor physics? [new operators above 10^4 GeV?]
 - neutrino masses and mixing? [see-saw at 10^{11} GeV?]
 - matter–antimatter asymmetry? [universe mostly matter]
 - gauge–coupling unification? [almost perfect, but proton stable]
 - gravity? [mostly negligible but perturbatively non-renormalizable]
- ⇒ **cut-off scale unavoidable: SM effective theory**

Standard–Model effective theory

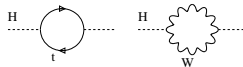


Consistency of fundamental theory

- remember: fundamental Higgs to save gauge theories at high energies
- problem of light Higgs: mass driven to cutoff of effective Standard Model
$$\delta m_H^2 \propto g^2/m_W^2 (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2) \Lambda^2$$
- cancelled by counter term, cosmological constant tuned anyway but problems not linked [‘weakless universe’: Harnik, Kribs, Perez]
- or new physics at TeV scale:
 - supersymmetry [my favorite]
 - extra dimensions [cool idea]
 - little Higgs [old idea, now working]
 - composite Higgs, no Higgs... [tough]

⇒ fundamental Higgs without TeV–scale completion useless

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Standards of model building

- many new states around the TeV scale [subject to experimental constraints]
- discrete symmetry for e-w precision constraints, proton decay
- stable lightest new particle: dark matter [weakly coupled, below TeV range]
- additional symmetries for flavor constraints

⇒ general: TeV–scale models in baroque state

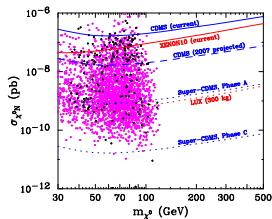
Effective Standard Model in the LHC era

Expectations from the LHC [Uli Baur's rule: 'there is always new physics at higher scales']

- find light Higgs?
- find new physics stabilizing Higgs mass?
- see dark-matter candidate?

Particle theory and new physics

- model-independent analyses likely not helpful
- testing testable hypotheses [theory: e.g. Higgs sector and underlying theory?]
 - discrete hypotheses: spins,....
 - continuous hypotheses: masses,...
- link to other observations [DM+Tevatron: Hooper, TP, Valinotto]
- reconstruction of Lagrangian [theory+experiment]



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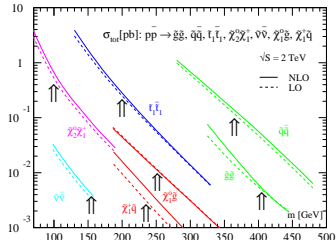
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Special about LHC [except bigger than Tevatron]

- beyond inclusive searches [that was Tevatron]
 - lots of strongly interacting particles cascade decays to DM candidate
 - general theme: try to survive QCD
- ⇒ **aim at underlying theory**



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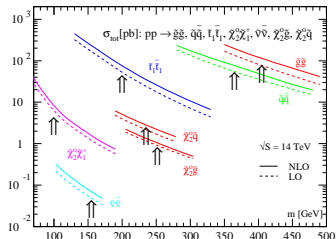
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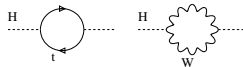
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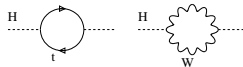
TeV-scale supersymmetry



Supersymmetry

- give each Standard-Model particle a partner [different spin, valid to all orders]
 - SUSY obviously broken by masses [soft breaking, mechanism unknown]
 - sooo not an LHC paradigm: maximally blind mediation [MSUGRA, CMSSM]
scalars — m_0 fermions — $m_{1/2}$ tri-scalar — A_0 Higgs sector — $\text{sign}(\mu), \tan \beta$
 - assume dark matter, stable lightest partner
- ⇒ **measure BSM spectrum with missing energy at LHC**

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LHC searches: MSSM

- conjugate Higgs field not allowed
 - give mass to t and b ?
 - five Higgs bosons
 - SUSY-Higgs alone interesting...
 - ...(1) new heavy Higgs states
 - ...(2) really type-II 2HDM
 - ...(3) light state MSSM vs SM
 - ...but another talk
- ⇒ list of SUSY partners

		spin	d.o.f.	
fermion	f_L, f_R	1/2	1+1	
→ sfermion	\tilde{f}_L, \tilde{f}_R	0	1+1	
gluon	G_μ	1	n-2	
→ gluino	\tilde{g}	1/2	2	Majorana
gauge bosons	γ, Z	1	2+3	
Higgs bosons	h^0, H^0, A^0	0	3	
→ neutralinos	$\tilde{\chi}_i^0$	1/2	4 · 2	LSP
gauge bosons	W^\pm	1	2 · 3	
Higgs bosons	H^\pm	0	2	
→ charginos	$\tilde{\chi}_i^\pm$	1/2	2 · 4	

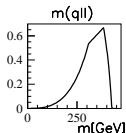
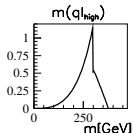
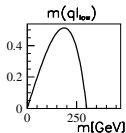
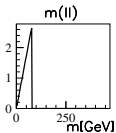
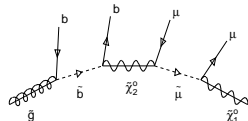
Masses from cascades

Cascade decays [Atlas-TDR, Cambridge]

- if new particles strongly interacting and LSP weakly interacting
- like Tevatron: jets + missing energy
- tough: $(\sigma BR)_1 / (\sigma BR)_2$ [unavoidable: focus point]
- easier: cascade kinematics [10⁷ . . . 10⁸ events]
- thresholds & edges

$$0 < m_{\mu\mu}^2 < \frac{m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2}{m_{\tilde{\ell}}} \frac{m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\ell}}}$$

⇒ new-physics mass spectrum from cascade kinematics



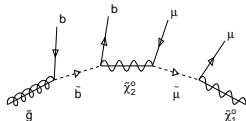
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Glauino decay [Gjelsten, Miller, Osland]

- all decay jets b quarks [otherwise dead by QCD]
- no problem: off-shell [Catpiss: Hagiwara et al.]

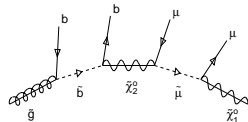
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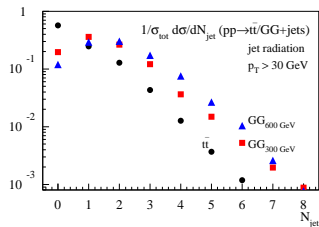
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Likely bad ideas

- decay jets vs QCD radiation
- collinear initial state radiation [$p_{T,j} < M_{\text{hard}}$]
- proper description: CKKW/MLM [in MadEvent]
- $\langle N_{\text{jet}} \rangle$ dependent on hard scale
- study: scalar gluons [TP & Tait]

⇒ QCD basics always useful at LHC



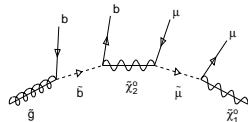
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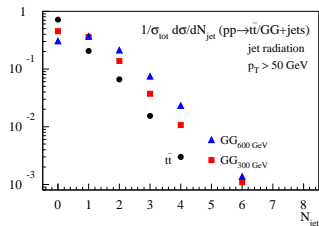
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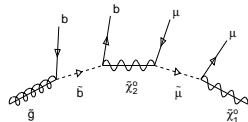
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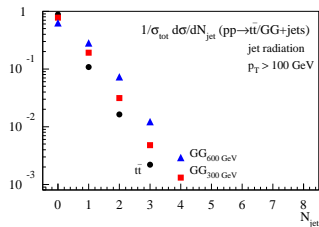
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Underlying parameters

From kinematics to weak-scale parameters [Fittino; SFitter: Lafaye, TP, Rauch, Zerwas]

- parameters: weak-scale Lagrangian
- measurements: kinematic endpoints, rates, flavor, dark matter,...
- errors: general correlation, statistics & systematics & theory [flat theory errors!]
- problem in grid: huge phase space, no local maximum?
problem in fit: domain walls, no global maximum?
problem in interpretation: bad observables, secondary maxima?

Probability maps of new physics [Baltz,...; Roszkowski,...; Allanach,...; SFitter]

- fully exclusive likelihood map $p(d|m)$ over m [hard part]
- LHC problem: remove pathetic directions [e.g. endpoints or dark matter vs rates]
- Bayesian: $p(m|d) \sim p(d|m) p(m)$ with theorists' bias $p(m)$ [cosmo, BSM]
frequentist: best-fitting point $\max_m p(d|m)$ [flavor]
- LHC era: (1) compute high-dimensional map $p(d|m)$
(2) find and rank local maxima in $p(d|m)$
(3) Bayesian–frequentist dance to reduce dimensions



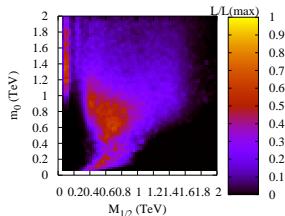
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MSUGRA as of today [Allanach, Cranmer, Lester, Weber]

- ‘Which is the most likely parameter point?’
- ‘How does dark matter annihilate/couple?’

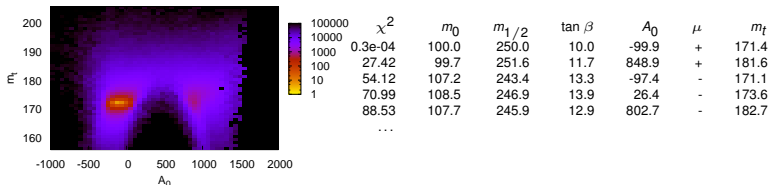


Underlying parameters

Toy model: MSUGRA map from LHC [LHC endpoints with free y_t]

- SFitter output #1: fully exclusive likelihood map
- SFitter output #2: ranked list of local maxima
- strong correlation e.g. of A_0 and y_t [including all errors]

⇒ correlations and secondary maxima significant



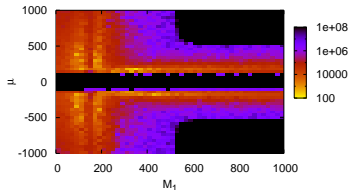
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MSSM map from LHC

- let's do physics instead of religion [unless God told you how she breaks SUSY]
- shifting from 6D to 19D parameter space [killing grids, Minuit, laptop-style fits...]
- SFitter outputs #1 and #2 still the same [weighted Markov chain plus hill climber]
- three neutralinos observed [profile likelihood]



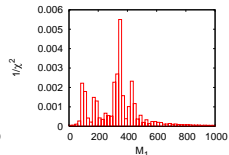
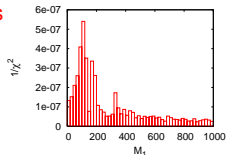
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 - three neutralinos observed [left: Bayesian — right: likelihood]
- ⇒ no golden approach to statistics



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Why theorists involved?

- want to learn statistics [usually get that badly wrong]
- theory errors not negligible [rates for focus–point scenarios]
- LHC link with other TeV–scale observations model dependent

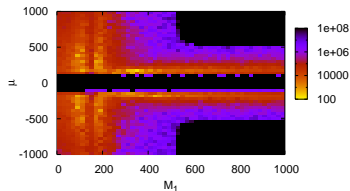
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MSSM parameters beyond LHC

- remember: unknown $\text{sign}(\mu)$, believe–based $\tan \beta$ from m_h
- LHC rates: $\tan \beta$ from heavy Higgs tough [Kinnunen, Lehti, Moortgat, Nikitenko, Spira]



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- (1) use current precision on $(g - 2)_\mu \sim \tan \beta$ [SFitter + Alexander, Kreiss]
- **strongly correlated and promising**

	LHC		LHC $\otimes (g - 2)$		SPS1a
$\tan \beta$	10.0 \pm	4.5	10.3 \pm	2.0	10.0
M_1	102.1 \pm	7.8	102.7 \pm	5.9	103.1
M_2	193.3 \pm	7.8	193.2 \pm	5.8	192.9
M_3	577.2 \pm	14.5	578.2 \pm	12.1	577.9
$M_{\tilde{\mu}_L}$	193.2 \pm	8.8	194.0 \pm	6.8	194.4
$M_{\tilde{\mu}_R}$	135.0 \pm	8.3	135.6 \pm	6.3	135.8
$M_{\tilde{q}_3L}$	481.4 \pm	22.0	485.6 \pm	22.4	480.8
$M_{\tilde{b}_R}$	501.7 \pm	17.9	499.2 \pm	19.3	502.9
$M_{\tilde{q}_L}$	524.6 \pm	14.5	525.5 \pm	10.6	526.6
$M_{\tilde{q}_R}$	507.3 \pm	17.5	507.6 \pm	15.8	508.1
m_A	406.3 $\pm \mathcal{O}(10^3)$		411.1 $\pm \mathcal{O}(10^2)$		394.9
μ	350.5 \pm	14.5	352.5 \pm	10.8	353.7

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 - **strongly correlated and promising**
- (2) use $\text{BR}(B_s \rightarrow \mu\mu)$ with stop–chargino sector [Hisano, Kawagoe, Nojiri]
 - 7% error on f_{B_s} by 2015 crucial [Della Morte, Del Debbio; SFitter + Jäger, Spannowsky]
 - **perturbative effects secondary**

	no theory error			$\Delta\text{BR}/\text{BR} = 15\%$	
	true	best	error	best	error
$\tan \beta$	30	29.5	3.4	29.5	6.5
M_A	344.3	344.4	33.8	344.3	31.2
M_1	101.7	100.9	16.3	100.9	16.4
M_2	192.0	200.3	18.9	200.3	18.8
M_3	586.4	575.8	28.8	575.8	28.7
μ	345.8	325.6	20.6	325.6	20.6
$M_{\tilde{t},R}$	430.0	400.4	79.5	399.8	79.5

Underlying parameters

Why theorists involved?

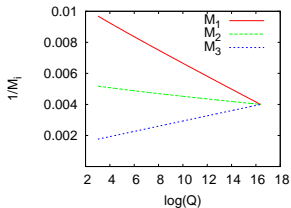
- want to learn statistics [usually get that badly wrong]
- theory errors not negligible [rates for focus-point scenarios]
- LHC link with other TeV-scale observations model dependent

MSSM parameters beyond LHC

- remember: unknown $\text{sign}(\mu)$, believe-based $\tan\beta$ from m_h
 - LHC rates: $\tan\beta$ from heavy Higgs tough [Kinnunen, Lehti, Moortgat, Nikitenko, Spira]
- (1) use current precision on $(g-2)_\mu \sim \tan\beta$ [SFitter + Alexander, Kreiss]
 - **strongly correlated and promising**
 - (2) use $\text{BR}(B_s \rightarrow \mu\mu)$ with stop-chargino sector [Hisano, Kawagoe, Nojiri]
 - 7% error on f_{B_s} by 2015 crucial [Della Morte, Del Debbio; SFitter + Jäger, Spannowsky]
 - **perturbative effects secondary**

Renormalization group bottom-up [SFitter + Kneur]

- SUSY breaking, unification, GUT?
 - scale-invariant sum rules? [Cohen, Schmalz]
- ⇒ **solidly inference from weak scale**

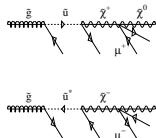


Spins from cascades

Glunos: strongly interacting Majorana fermions [Barger,...; Barnett,...; Baer,...]

- LHC: first jet (q or \bar{q}) fixes lepton charge
- same-sign dileptons in 1/2 of events
- similar: t -channel gluino in $pp \rightarrow \tilde{q}\tilde{q}$

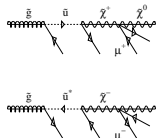
⇒ gluino = like-sign dileptons in SUSY sample



Spins from cascades

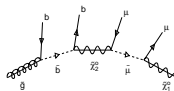
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Loop hole: gluino is Majorana if fermion

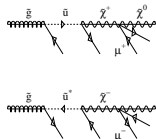
- all new physics is hypothesis testing [Barr, Lester, Smillie, Webber]
- physics between cascade endpoints
- model-independent analysis unlikely [Smillie]



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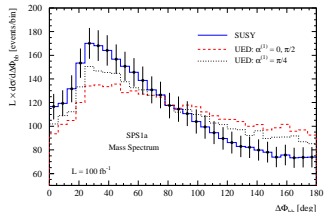


Loop hole: gluino is Majorana if fermion

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- 'gluino' a boson: universal extra dimensions [spectra degenerate, cross sections, higher KK states — ignore]
- compare SUSY with excited KK g, b, Z, ℓ, γ
- simple distributions [3-body decays: Csaki,...]
- threshold behavior? [under study]

\Rightarrow **gluino = fermion with like-sign dileptons**

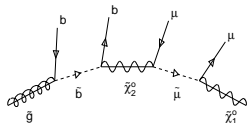


Spins from cascades

Elegant LHC universe [Alves, Eboli, TP; like Cambridge squarks]

- remember: spins mean angular correlations
- 'invariant angles': $m_{j\ell} / m_{j\ell}^{\max} = \sin \theta / 2$
- squark: production asymmetry $pp \rightarrow \tilde{q} / \tilde{q}^* + \tilde{g}$

$$\mathcal{A}(m_{j\ell}) = \frac{\sigma(j\ell^+) - \sigma(j\ell^-)}{\sigma(j\ell^+) + \sigma(j\ell^-)}$$



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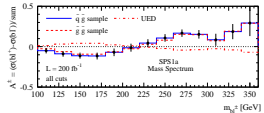
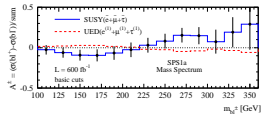
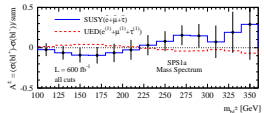
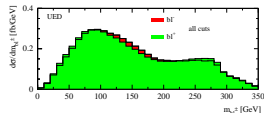
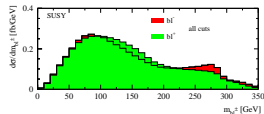
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- b vs. \bar{b} : example for advanced LHC requirement
- stable w.r.t production channels and cuts



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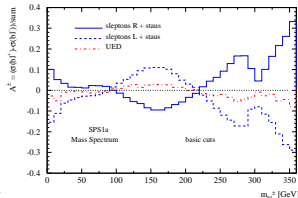
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- b vs. \bar{b} : example for advanced LHC requirement
- stable w.r.t production channels and cuts
- unstable w.r.t model details
- all messy once neutralinos and charginos involved
- positive: use information [Hagiwara, Kim, Mawatari, Zerwas]

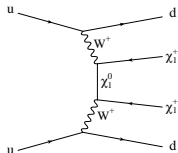
⇒ LHC only as good as understood hypotheses



Spins from jets

Illustrating testable hypotheses: spin of LSP [Alwall, TP, Rainwater]

- Majorana LSP with like-sign charginos?
 - hypotheses: like-sign charginos (SUSY)
 - like-sign scalars (scalar dark matter)
 - like-sign vector bosons (little-Higgs inspired)
 - chargino decay/kinematics not used
- ⇒ WBF : two key distributions $\Delta\phi_{jj}, p_{T,j}$ [like $H \rightarrow ZZ \rightarrow 4\mu$ or WBF-Higgs]



Weak boson fusion and unitarity

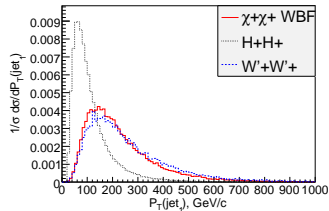
Like-sign scalars or fermions?

- charged Higgs in 2HDM
- H^+H^- same as simple H^0 [TP, Rainwater, Zeppenfeld; Hankele, Klamke, Figy]
- W radiated off quarks [Goldstone coupling to Higgs]

$$P_T(x, p_T) \sim \frac{1 + (1-x)^2}{2x} \frac{1}{p_T^2}$$

⇒ scalars with softer $p_{T,j}$

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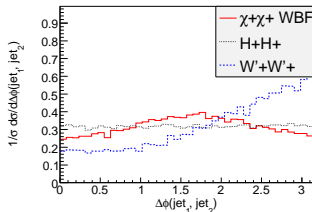
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Like-sign vectors or fermions?

- little-Higgs inspired
- start with copy of SM, heavy W', Z', H', f' [H' necessary for unitarity, but irrelevant at LHC]
- Lorentz structure reflected in angle between jets

⇒ vectors with peaked $\Delta\phi_{jj}$



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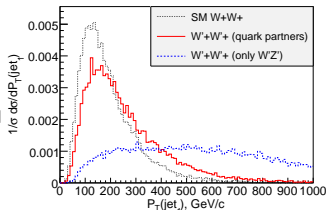
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Heavy fermions in little-Higgs models

- part of unitary UV completion [Englert, Zeppenfeld]
- huge effects on distributions [at low scales]

⇒ more like strongly interacting W s



New physics at the LHC

TeV-scale new physics at LHC

- know there is BSM physics [dark matter,...]
- solve hierarchy problem
- explain dark matter



Understanding the TeV scale

- (0) avoid getting killed by QCD
 - (1) look for solid new-physics signals [missing energy?]
 - (2) test sensible new-physics hypotheses
 - (3) measure weak-scale Lagrangian [highD parameter spaces?]
 - (4) determine fundamental physics [supersymmetry just example]
- ⇒ **LHC more than a discovery machine!**

**What to do with all
that LHC data**

Tilman Plehn

Why BSM?

Supersymmetry

Masses

Parameters

Spins & cascades

Spin & jets